The Effect of Multipath on Single Frequency C/A Code Based GPS Positioning

Thilantha Lakmal Dammalage
Department of Remote Sensing and GIS
Faculty of Geomatics
Sabaragamuwa University of Sri Lanka
Belihuloya, Sri Lanka
thilantha@geo.sab.ac.lk

***Abstract*—The differential GPS (DGPS) technique is one of the most popular and comparatively accurate techniques available to enhance the positioning accuracy by minimizing most of the common errors. However, the ultimate accuracy of the user location depends on the remaining non-common errors (multipath, receiver clock, and noise), which occur at the points of observation and reference. Out of these errors, multipath is the most dominant and challenging error to predict and minimize. Single frequency C/A code based GPS receivers are popular due to their comparatively low cost compared to dual frequency (L1/L2) GPS receivers. This paper focuses on evaluating the effect of multipath error on single frequency C/A code based GPS positioning. For the analysis, 72,000 continuous GPS observations with one-second interval under four different multipath environments were conducted by utilizing three geodetic GPS units. Accordingly, the observations with more than 5cm on the 2D positional error, created by the effected multipath, were always less than 25%. Here, an average of 16% of observations exceeded 20cm in 2D positional error. Further, it was noted that the presence of multipath introduces significantly higher and comparatively lower 3D positional errors on DGPS observations. This could be due to the compensation of negative and positive effects caused by the multipath and other remaining non-common mode errors at the reference and user stations. In addition, C/A code based single frequency GPS observations were significantly influenced by multipath, not only by the close-by reflectors but also by the ground surface. The effect of multipath was about 50% of the total 3D positional error for the four tested multipath environments.**

Keywords-C/A code observations; DGPS; multipath

I. Introduction

Global positioning system (GPS) developed by the US Department of Defense, was first planned to have 24 satellites in operation. Each of the satellites continuously transmitted two high-frequency carrier waves L1 and L2, with frequencies of 1575.42MHz and 1227.60MHz respectively [1]. C/A-code (coarse-acquisition) is for civilian users and P-code (precision) for U.S. military or authorized users. The code signals are superimposed on the L1 carrier, while L2 carries only the P-code [2]. Both codes allow a GPS receiver to measure the signal propagation time from satellites to the receiver instantaneously using the distance from satellites to the receiver, (pseudo-range). Pseudo-ranges are then utilized for the estimation of GPS receiver position [3]. Basically, there are two forms of observations depending on the capability of the receivers to process C/A code and L1/L2 carriers, referred to as code and carrier range observations respectively [4]. Therefore, GPS based positioning accuracy directly depends on the accuracies of calculated ranges to at least four satellites [5]. Most of the presently available GPS receivers utilize almost all the state-of-the-art technical improvements in GPS hardware and processing algorithms. However, still these GPS receivers suffer from significant positioning errors due to signal propagation delays through ionosphere and troposphere, satellite and receiver clock errors, bias on ephemeris data, multipath, and receiver and measurement noises [6-8]. Hence, the standard positioning service (SPS) accuracy widely varies with time, place, and most importantly, GPS receiver performance [2]. These measurement errors are generally classified as either common or non-common mode errors. The common errors (ionosphere delay, troposphere delay, satellite clock, and bias on ephemeris data) have similar effects on all receiver measurements operating in a limited geographic area [7]. Non-common mode errors (multipath, receiver, and measurement noises) are distinctive and the amount of their influence depends on the surrounding obstructions at the observation site and the technical specification of receivers [9].

Numerous techniques are available to minimize the above-listed sources of errors from GPS position estimation. A user equipped with a dual frequency (L1, L2) GPS receiver can estimate the ionospheric group delay and phase advance from the measurements themselves, and virtually eliminate the ionosphere as a source of error [10, 11]. Besides, many different models have been proposed to quantify the effect of ionospheric and tropospheric delay on GPS measurements. The Klobuchar model is one of the popular empirical models, which uses the satellite broadcast parameters to estimate the propagation zenith ionospheric delay [12]. There is no dearth of tropospheric models, in particular, the Saastamoinen model, which was derived based on the gas laws and simplifying assumptions regarding changes in pressure, temperature, and humidity with altitude [13]. However, none of these models can precisely estimate the total effect on measurements and most of them always require additional parameters such as local metrological data. Some GPS receiver-operation and data-processing software offered at a price, however, can be employed to overcome these drawbacks.

Differential correction (DGPS) is one of the most popular and comparatively accurate techniques to enhance GPS positioning accuracy by minimizing most of the common mode errors as a combined operation [6]. In this technique, a reference station, the position of which is accurately known, is utilized to determine the magnitude of common mode errors, which are then applied to other GPS observations to minimize these errors by assuming they were equally affected for both stations. The extent to which DGPS reduces common mode errors depends on various factors; mainly the separation of reference and user GPS receivers [14, 15]. It, sometimes, limits the assumption of common environmental conditions which affect both receivers. Furthermore, DGPS accuracy is also highly dependent on the GPS receiver type, which varies with the capability of utilizing carrier and/or code measurements for the position solution. DGPS technique has been classified into two categories, namely carrier phase based and code based DGPS, where the accuracies vary from centimeter-level to meter-level respectively [4]. Several DGPS processing techniques are available. For instance, single difference and double difference, which are very common in practice, yet depend on the capability of the receiver and processing software [16]. Whatever the processing technique used in DGPS, the ultimate accuracy of the user location depends on the amount of residual common mode errors and the combined effect of non-common mode errors at the reference point and the point of observation. Of the latter, the dominant mode has been identified to be the multipath, which is named after the multiple receptions of one satellite signal due to reflections by surrounding objects.

II. MULTIPATH ERROR

Multipath is caused by GPS signals reflected from surfaces near the GPS antenna, which could be mistaken as the signal that follows the direct path from the satellite [17]. Any obstructions in the surrounding vicinity of the GPS antenna have higher possibility to diminish the positional accuracy in many ways [18]. Therefore, as a thumb-rule, it is considered that the ideal conditions for GPS observations are a clear view of the sky with no obstructions at least for about 5 degrees elevation and up. However, in practical conditions, for instance, due to Earth's surface (ground and water), buildings, trees, fences, and cables, free observation sites are rare. The diverse nature and complex behavior of multipath signals cause its mathematical representations extremely difficult and cumbersome [19]. The effect of multipath on the carrier phase signal is demonstrated only by using a planar vertical reflection surface at distance d from the GPS antenna. Figure 1 presents the respective geometry [15]. Accordingly, the direct line-of-sight carrier phase measurement (Φ_D) for satellite "s" based on L1 frequency can be represented as in (1):

$$\Phi_D^{s,L1} = A\cos\phi \tag{1}$$

where A and ϕ denote the amplitude (voltage) and the phase of the signal respectively.

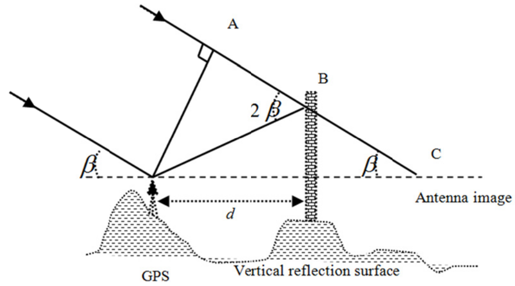

Fig. 1. Geometrical representation of multipath effect by a vertical surface

The carrier phase measurement (Φ_R) based on the reflected signals of the same satellite can be written as:

$$\Phi_R^{s,L1} = \alpha A\cos(\phi+\delta\phi),\ for\ 0 \le \alpha \le 1 \tag{2}$$

where $\alpha = A'/A$, α is the attenuation (amplitude reduction factor) and A' is the amplitude of the reflected signal, and $\delta\phi$ is the phase shift due to reflection.

$$\delta\phi = f\Delta\tau + \varphi \tag{3}$$

where f is the frequency, $\Delta\tau$ is the time delay, and φ is the fractional shift.

With reference to Figure 1, the total multipath delay is the sum of distance AB and BC, which equals to $2d\cos\beta$. By converting this distance into phase cycles and then to radians, the phase shift ($\delta\phi$) can be calculated as

$$\delta\phi = \frac{4\pi d}{\lambda}\cos\beta + \varphi \tag{4}$$

where, λ is the wavelength of the carrier signal. The composite signal at the antenna is then the sum of the direct and reflected signal:

$$\Phi = \Phi_D + \Phi_R = R\cos(\phi + \Psi) \tag{5}$$

where, R is the resultant carrier phase voltage which is a function of A, α and $\delta\phi$ and Ψ is the carrier phase multipath delay which is a function of α and $\delta\phi$. The notations for frequency (L1, L2) and satellite ID (s) are neglected to minimise the complexity of representation.

By solving the previously derived (4) and (5), the resultant carrier phase multipath delay can be verified as;

$$\Psi(\alpha,\delta\phi) = \tan^{-1}\frac{\alpha\sin\delta\phi}{1+\alpha\cos\delta\phi} \tag{6}$$

However, the pseudo-range multipath error (M_ρ) is simple in representation as in (7), and it is valid for both P-code and C/A-code as long as the appropriate chipping period is used.

$$M_\rho = c\Delta\tau_\rho \tag{7}$$

Furthermore, a derivation for pseudo-ranges multipath effect based on carrier phase and pseudo-range measurements were derived in [20], taking advantage of the fact that multipath and noise on carrier phase measurments are negligible compared to those of pseudo-range. Equations (8) and (9) respectively represent the pseudo-range multipath based on L1 and L2 frequencies.

$$M_{\rho}^{L1} = PR^{L1} - \frac{9529}{2329}\Phi^{L1} + \frac{7200}{2329}\Phi^{L2} + K_1 \quad (8)$$

$$M_{\rho}^{L2} = PR^{L2} - \frac{11858}{2329}\Phi^{L1} + \frac{9529}{2329}\Phi^{L2} + K_2 \quad (9)$$

where, K1 and K2 are functions of the multipath on carrier phase and include the unknown integer ambiguities. The multipath effect is considered to be a combination of harmonic signals and can be averaged out to zero over a few hours. Therefore, K1 and K2 can be estimated by averaging over a period of few hours [21], and the result is the combination of pseudo-range multipath and receiver noise.

A reflected signal, delayed by more than 1.5 chips, would be censored automatically by the correlation process of the receiver, where the auto-correlation for the C/A-code is nearly zero for delays longer than 1.5 chips [22]. Such a delay corresponds to about 500m of increased path length for a C/A-code and 50m for P-code signal. The effect of a reflected signal delayed by less than 1.5 chips would depend upon the amount of delay and signal amplitude. Typical multipath error in pseudo-range measurements varies from 1m in a benign environment to more than 5m in a highly reflected environment. In some cases, it could reach even 100m [15]. However, the corresponding error in the carrier phase measurements is typically two orders of magnitude smaller (1-5cm [2]. It has been found that the error caused by multipath is highly variable in the time domain showing quasi-sinusoidal oscillations with a period of several minutes creating extreme difficulty in modeling it [21, 23]. The magnitude of C/A code multipath error is almost ten times greater than that of the carrier phase measurements [24]. Nevertheless, a wide range of GPS receivers, from low-cost to very expensive, offer code based DGPS corrections. Besides, the operational distance of code based DGPS is several hundreds of kilometres while the carrier phase DGPS operations are limited to several tens of kilometers [25]. In addition, single frequency C/A code based GPS receivers are common in use due to their comparatively low cost compared to dual frequency GPS receivers. Considering the practical advantages and the significant effect of a multipath error on C/A code measurements, authors in [8] investigated the mitigation of the multipath effect on DGPS corrections that are generated by a permanent GPS reference station. They used a carrier phase and pseudo-range measurements for the derivation of pseudo-range multipath effect (M_{ρ}), which was formulated in [20], based on L1 and L2 frequencies as represented by (8) and (9). Based on this, a successful attempt was made to precisely estimate the pseudo-range (C/A code) multipath error at permanent GPS reference stations. The experiment presented in this paper also utilizes the method proposed in [8] for multipath estimation and mitigation from observations. However, the primary focus of this paper is to analyze the effect of the multipath error on single frequency C/A code based GPS positioning.

III. FIELD EXPERIMENT

A field experiment was designed, and observations were made to analyze the multipath effect on single frequency C/A code based GPS positioning. Three dual-frequency geodetic-type GPS receivers were mounted over three precisely fixed ground control points to accomplish the configuration illustrated in Figure 2.

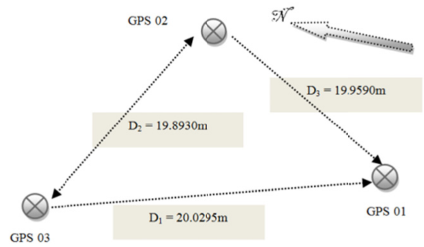

Fig. 2. GPS receiver configuration in the field experiment

A Trimble 5700 L1/L2 receiver was utilized at station GPS 03, and the observations at stations GPS 01 and 02 were conducted using two LEICA – System 500 instruments. The lengths between each ground control points were measured by an Electronic Distance Measurement (EDM) instrument. The observed distances were, D1=20.0295m, D2=19.8930m and D3=19.9590m. These precisely known measurements were used as ground truth to validate the accuracy of the results obtained throughout this experiment. The experiment site selected had minimum obstructions for satellite signals even for satellites at very low elevations (~10^0). The selected site had 360^0 undisturbed open sky view and was situated on elevated, flat ground. There were no buildings, electric cables, water bodies and concrete, mettle, or wood surfaces found at the site proximity. Hence, this site configuration assumed to be as a benign multipath environment for GPS observations. For the multipath effect analysis, three different artificially designed multipath environments were introduced for GPS 01 observation for three consecutive days. Four-sets of 20-hour observations with 1-second interval were conducted by generating additional multipath by concrete, wood, and metal reflectors. The last set was observed without any reflector at GPS 01 station. Figure 3 illustrates the field set up for observations with reflectors. The concrete reflector was constructed at the outset for the first set of 20-hours of day 1 observations, and then the surface of the same reflector was changed for day 2 and 3 observations by placing wood and metal sheets at the direction of GPS receiver. The reflector location, size, and orientation were maintained unchanged throughout day 1, 2, and 3 observations, to minimize the bias due to the change of multipath environment. Last, observations of day 4 were conducted without any reflector at GPS 01, however, the GPS receiver antenna height and location were maintained unchanged.

IV. RESULT ANALYSIS

The contribution of common mode errors has to be reduced to minimum to analyze the effect of multipath on GPS observations. Therefore, C/A code based DGPS processing was conducted by assuming GPS 03 as the reference station, and GPS 01 and 02 as users/rovers. Due to the very short baseline distances, this accuracy analysis assumed that no residual common mode errors remain on differentially corrected observations. Hence, the possible inaccuracies of the resulted coordinates are the effect of non-common mode errors, out of which the multipath effect is the most significant. According to the arrangement of the observation site, the possible source of multipath error at GPS01 was the reflector and/or the ground surface.

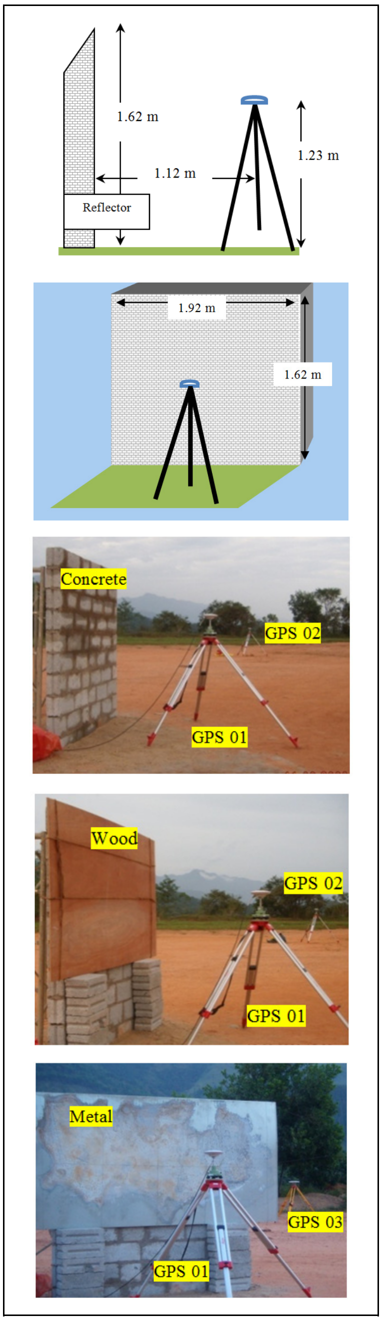

Fig. 3. Reflector configuration at GPS 01 station

At GPS02 and 03, the only possible source was the ground surface. A Trimble 5700 receiver was used at GPS03 with a Zephyr Geodetic L1/L2 antenna and Trimble Stealth ground plane technology, which could reduce most of the multipath created from the ground surface. Therefore, the negative influence that could be introduced by multipath on DGPS corrections generated at GPS03 reference station is assumed to be minimum. To evaluate the effect of multipath on C/A code based GPS positioning, 2D and 3D positioning accuracies at GPS1 and GPS2 were comparatively analyzed by utilizing the accurately measured baseline distances with GPS3 reference station.

A. Effect on 2D Positioning

The multipath effect is analyzed by evaluating the 2D positional accuracy of 72,000 observations recorded for 20-hours with a 1-second interval. Table I presents the number of observations as a percentage of total records, within four different 2D positional error limits, less than or equal to 5cm, greater than 5cm, and greater than or equal to 20cm and 50cm (<5cm, >5cm, >20cm, and >50cm). The effect of multipath is calculated for both baselines, BL1 (GPS 03 – GPS 01) and BL2 (GPS 03 – GPS 02), as reported in Table I.

TABLE I. OBSERVATION PERCENTAGE AT 2D POSITIONAL ERROR CAUSED BY MULTIPATH

Observation		2D positional error due to multipath			
		≤5cm	>5cm	≥20cm	≥50cm
Day1	BL1	78.4%	21.6%	16.0%	7.6%
	BL2	80.1%	19.9%	04.1%	1.8%
Day2	BL1	79.1%	20.9%	16.1%	6.8%
	BL2	89.9%	10.1%	03.6%	0.5%
Day3	BL1	75.4%	24.6%	17.3%	9.3%
	BL2	84.7%	15.3%	3.8%	1.5%
Day4	BL1	79.3%	20.7%	06.7%	0.4%
	BL2	84.4%	15.6%	02.6%	0.7%

Observations with the 2D positional error of less than or equal to 5cm could be considered as observations that are comparatively low affected by multipath. An average of about 78% and 85% were recorded with minimum multipath error for baselines BL1 and BL2 respectively. In addition, an average of about 22% and 15% observations were affected by higher multipath errors (more than 5cm of 2D positional errors for baselines BL1 and BL2 respectively). According to the condition of the observation site, the possible source of error for BL1 is the multipath at GPS01 created by the reflector and/or the ground surface. For BL2 it is the multipath at GPS02 created by the ground surface. Therefore, the percentage difference between BL1 and BL2 represents the additional multipath introduced by the artificial reflector separately from the ground. Accordingly, the artificial reflectors introduced both lower and higher than 5cm multipath errors on average of 7%. The highest difference percentage was observed for 2D positional error limit more than or equal to 20cm. When compared to the observations without reflector at GPS 01, the artificially-generated multipath diminished. However, for 2D positional error limit of more than or equal to 20cm, the number of observations were improved by 9.3%, 9.4%, and 10.6% over the observations without a reflector for concrete, wood, and metal, reflectors respectively. This confirms that the amount of multipath effect changes with the material of the reflector and is significant for higher 2D positional errors of greater than 20cm on C/A code based GPS observations.

B. Effect on 3D Positioning

Further analysis was conducted to investigate the effect of the multipath error on 3D positioning with single frequency

C/A code based GPS observations. In order to analyze the effect of multipath generated by the reflectors at GPS 01, a 3D positional error was calculated for 10 hours of observations with a 1-second interval. Also, the 3D positional error was calculated before and after the multipath mitigation from pseudo-range observations before DGPS baseline processing. Multipath residuals were calculated based on (8) and (9) and mitigated from GPS 01, 02, and 03 observations by adopting the methodology proposed in [8]. The resulted time-series 3D positional errors are presented in Figure 4 as before and after multipath mitigation for baselines BL1 (GPS 03 – GPS 01) and BL2 (GPS 03 – GPS 02), where, GPS 03 was used as the reference station. The red lines present the error before multipath mitigation and the blue ones the error after multipath mitigation. The time-series of 3D positional errors for each respective day of observations between BL1 and BL2 before pseudo-range multipath mitigation have not shown any similarity to each other, even for day 4 observations with no reflector. However, after multipath mitigation, the time-series of 3D positional errors for each day of observations between BL1 and BL2 were significantly correlated. Based on this, it can be concluded that the remaining un-modeled common and non-common mode errors for BL1 and BL2 after multipath mitigation were almost similar.

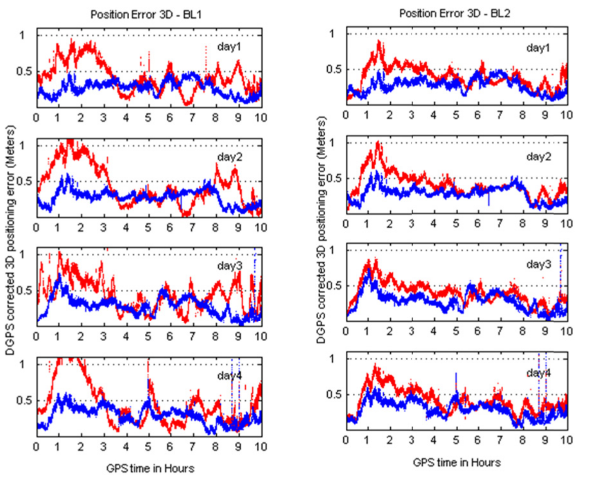

Fig. 4. 3D positional accuracy comparison before and after multipath mitigation

The common reference station used for both of these two very short baseline observations and the use of the same type of receiver at both user stations could be the main reasons. However, the time-series of 3D positional errors have not shown any significant correlation between the different days for both BL1 and BL2. This provided evidence that the remaining 3D positional errors even after DGPS correction and multipath mitigation are not systematic, they are random and changing with time and day. The un-modeled common and non-common mode errors, both at the reference and user, could be the possible sources of these remaining 3D positional errors. The comparison of time-series of the 3D positional errors calculated before multipath mitigation revealed another significant deviation between BL1 and BL2 positional accuracies. For BL2, the error after multipath mitigation was always lower than that before, but this was not always true for BL1. Surprisingly, for some time intervals, the 3D positional error before multipath mitigation was better than that after multipath mitigation. Therefore, it can be concluded that the presence of multipath not only introduces significantly higher 3D positional errors but also comparatively lower errors on GPS observations. This could be caused by the error compensation of negative and positive effects caused by multipath and other remaining non-common mode errors at the reference and user stations.

According to the observation setup, the only possible source of multipath at the reference station was the ground surface. However, with the use of Trimble stealth ground plane technology at the GPS03 reference station, the effect of multipath on its DGPS corrections could be easily minimized. Therefore, the contribution of multipath effected at the reference station, to the differentially corrected observations, is assumed to be minimum. Based on which, the real effect of the multipath error on C/A code based GPS observations was calculated by subtracting the 3D positional error after multipath mitigation from the one before by assuming that the un-modeled common and non-common mode errors remain the same before and after multipath mitigation. The resulted true multipath error effected the user observations. The percentage of true multipath error concerning the total error remaining even after C/A code based DGPS processing is presented in Figure 5. The same 10 hours of observations presented in Figure 4 is utilized for the calculations. Comparative analysis revealed that multipath contributes about 50% of the total 3D positional error of single frequency C/A code based GPS observations. The magnitude of the multipath effect on 3D position solution varies with the time of observation and the condition of the multipath environment. In general, multipath has a significant influence on single frequency C/A code based on GPS observations even at favorable multipath environment.

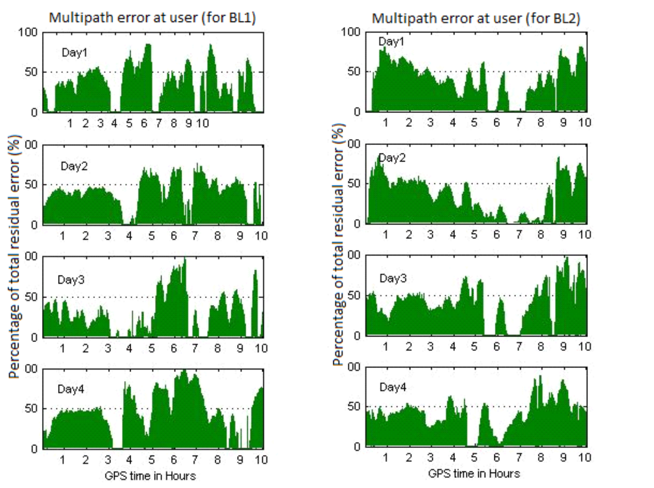

Fig. 5. Multipath error as a percentage of total remaining error after C/A code based DGPS observations

V. Conclusion

This paper presented the multipath effect on single frequency C/A code based GPS positioning by comparatively analyzing the 2D and 3D positioning accuracies after DGPS processing. Based on the analysis, averages of 22% and 15% of the tested 72,000 observations were recorded with higher multipath errors of more than 5cm on 2D positioning for all the tested multipath conditions of baselines BL1 and BL2 respectively. It has observed that the magnitude of multipath error changed with the material of the reflector and was significant for higher 2D positional errors, greater than 20cm on C/A code based GPS observations. Further, it was noted that the presence of multipath introduces not only significantly higher positional errors, but also comparatively lower errors on C/A code single frequency GPS observations. Compensation of negative and positive errors caused by the multipath and other remaining non-common mode of errors at the reference and user stations could be the main reason for the observed irregular variation. Multipath has a significant influence on single frequency C/A code based GPS observations, and for the tested observations, the contribution was about 50% of total 3D positional errors of single frequency C/A code based GPS observations.

REFERENCES

[1] I. A. Getting, "The Global Positioning System", IEEE Spectrum, Vol. 30, No. 12, pp. 36–47, 1993

[2] P. Misra, P. Enge, Global positioning system signals, measurements, and performance, Ganga-Jamuna Press, 2011

[3] B. W. Parkinson, "GPS Eyewitness: The Early Years", GPS World, Vol. 5, No. 9, pp. 32-45, 1994

[4] B. Hofmann-Wellenhof, H. Lichtenegger, J. Collins, GPS Theory and Practice, Springer Science & Business Media, 2012

[5] V. S. Jan, GPS for Land Surveyors (2nd ed.), Ann Arbour Press, 2001

[6] B. W. Parkinson, J. J. Spilker, Global Positioning System: Theory and Applications, American Institute of Aeronautics and Astronautics, Washington, USA, 1996

[7] G. Xu, Y. Xu, GPS Theory, Algorithms, and Applications, Springer-Verlag, 2003

[8] T. L. Dammalage, C. Satirapod, S. Kibe, C. Ogaja, "C/A Code multipath mitigation at GPS reference stations for improved differential GPS corrections", Survey Review, Vol. 42, No. 317, pp. 240-255, 2010

[9] E. M. Hill, J. L. Davis, P. Elosegui, B. P. Wernicke, E. Malikowski, N. A. Niemi, "Characterization of site-specific GPS errors using a short-baseline network of braced monuments at Yucca Mountain, southern Nevada", Journal of Geophysical Research: Solid Earth, Vol. 114, No. B11, 2009

[10] E. L. Afraimovich, V. V. Chernukhov, V. V. Demyan, "Updating the ionospheric delay model using GPS data", Application of the Conversion Research Results for International Cooperation. SIBCONVERS'99. Third International Symposium, Tomsk, Russia, pp. 455-457, May 18-20, 1999

[11] R. Giffard, "Estimation of GPS ionospheric delay using code and carrier phase observables", 31st Annual Precise Time and Time Interval (PTTI) Meeting, Dana Point, USA, December 7-9, 1999

[12] J. A. Klobuchar, "Ionospheric Effects on GPS", GPS World, Vol. 2, No. 4, pp. 48-51, 1991

[13] P. Collins, R. Langley, J. LaMance, "Limiting Factors in Tropospheric Propagation Delay Error Modelling for GPS Airborne Navigation", Institute of Navigation 52nd Annual Meeting, Cambridge, USA, June 19–21, 1996

[14] RTCM-SC104, RTCM recommended Standards for Differential GNSS (Version 2.3), Radio Technical Commission for Maritime Services, 2001

[15] A. Leick, GPS Satellite Surveying, John Wiley & Sons, 2004

[16] L. Baroni, K. H. Kuga, "Analysis of navigational algorithms for a real time differential GPS system", 18th International Congress of Mechanical Engineering, Ouro Preto, Brazil, November 6-11, 2005

[17] C. He, J. Guo, X. Lu, J. Lu, "Multipath performance analysis of GNSS navigation signals", Electronics Computer and Applications IEEE Workshop, Ottawa, Canada, pp. 379-382, 2014

[18] T. Kos, I. Markezic, J. Pokrajcic, "Effects of Multipath Reception on GPS Positioning performance", ELMAR-2010, 2010, Zadar, Croatia, September 15-17, 2010

[19] P. Karimi, F. Farzaneh, "Reduction of multi-path effect based on correlation decomposition in a DOA estimation system", Signal Processing and Intelligent Systems Conference, Tehran, Iran, pp. 10-14, IEEE, 2015

[20] S. Han, C. Rizos, "Multipath effects on GPS in mine environments", International Congress of the International Society for Mine Surveying, Fremantle, Australia, pp. 447-457, November 2-6, 1997

[21] L. Ge, S. Han, C. Rizos, "GPS Multipath Change Detection in Permanent GPS Stations", Survey Review, Vol. 36, No. 283, pp. 306-322, 2002

[22] R. D. Van Nee, J. Siereveld, P. C. Fenton, B. R. Townsend, "The multipath estimating delay lock loop: approaching theoretical accuracy limits", IEEE Position Location and Navigation Symposium, Las Vegas, USA, pp. 246-251, August 6, 1994

[23] K. K. Fan, X. L. Ding, "Estimation of GPS Carrier Phase Multipath Signals Based on Site Environment", Journal of Global Positioning Systems, Vol. 5, No. 1-2, pp. 22-28, 2006

[24] A. Mertins, Signal Analysis: Wavelets, Filter Banks, Time-Frequency Transforms and Applications. John Wiley, 1999

[25] T. L. Dammalage, P. Srinuandee, L. Samarakoon, J. Susaki, T. Srisahakit, "Potential Accuracy and Practical Benefits of NTRIP Protocol Over Conventional RTK and DGPS Observation Methods", Map Asia, Bangkok, Thailand, August 29 – September 1, 2006